

Cosmic Rays from Decaying Vortons

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Abstract

The flux of high energy cosmic rays coming from the decay of vortons is estimated. If the abundance of loops corresponding to a superconductivity scale coincident with that of the string formation is corrected to be compatible with the critical density of universe, it is found that the emission of one carrier per vorton may produce a flux of one cosmic ray event per km^2 of detector and per year.

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I. Introduction

It is difficult to explain the source of the observed ultra high energy cosmic rays (UHECR) exceeding a few 10^{19} eV [1].

Standard acceleration mechanisms hardly justify energies higher than 10^{15} eV [2]. It is possible that UHECR have an extragalactic origin in AGN, which cannot be however at a distance larger than 100 Mpc to avoid their degrading through pion photoproduction due to scattering with CBR [3].

For the case that these relatively nearby sources cannot be identified, an alternative explanation may be a top-down production of UHECR from Grand Unified Theories (GUT) particles emitted by topological defects like cosmic strings [4].

However, normal cosmic strings formed at the GUT scale suffer a dynamics which reduces their density at present in such a degree that the possible flux of cosmic rays that they may produce is several orders of magnitude lower than the expected one [5].

Cosmic strings may become more stable if they have a superconducting core [6]. When they are very long, their motion through the intergalactic magnetic field induces strong currents which favour the emission of a high mass carrier whose decay might produce the UHECR. But the extreme intense magnetic field surrounding the superconducting string would degrade the particle energy through synchrotron radiation.

A more plausible scenario is that of vortons, small superconducting closed strings stabilized by their angular momentum [7]. Their present density is determined classically by the scale at which they acquire the superconducting property [8] that is constrained by the primordial nucleosynthesis and the critical density of the universe [9].

In the present work we have estimated the flux of cosmic rays from quantum decay of vortons. The evaluation is based on the tunneling of a chiral vorton, with equal topological and charge numbers, to a configuration with one less unit. It is seen that vortons which acquire superconductivity at a scale much lower than that of GUT have a negligible probability of tunneling decay. But if instead superconductivity appeared at the string formation, quantum decay or other mechanisms may reduce vorton abundance to become consistent with the universe critical density and a flux of cosmic rays compatible with the expected one might be obtained.

In Section II we derive the expression of the UHECR flux from the density of vortons in terms of its lifetime which is estimated by a semiclassical method in Section III. Conclusions are given in Section IV.

II. The Flux of Cosmic Rays

As it was done in Ref.[5], using conformal time and space $ds^2 = a^2(\tau)(d\tau^2 - dx^2)$, the number of events in a spherical shell during a conformal time interval is

$$\langle n(\tau) \rangle > 4\pi a^2 x^2 \, dx \, d\tau \quad . \quad (1)$$

The fraction that will be observed by a detector of area A is $A/4\pi a_0^2 x^2$, where a_0 is the present scale.

If for each event there are N_c produced particles the present detected flux will be

$$\frac{1}{A} < \frac{d\mathcal{N}}{dt_0} > = \int_{t_{eq}}^{t_0} N_c \langle n(\tau) \rangle \frac{a^3}{a_0^3} dt \quad , \quad (2)$$

where the integration is extended back to the equivalence time between radiation and matter because beyond it the cosmic rays would have been too heavily redshifted, since $z_{eq} \sim a \text{ few } 10^4$, the eventually emitted GUT particle has a mass $M_X \sim 10^{24} \text{ eV}$ and we are interested in UHECR of energy greater than a few 10^{19} eV .

The number of events per unit volume and time would be related to the vorton density and lifetime for the decay mode of one carrier by $\langle n(\tau) \rangle = n_v / \tau_v$.

If one assumes that the scale for the appearance of superconducting properties coincides with that of the string formation $M_X \sim M_{GUT} = \eta$, the vorton density turns out to be classically [9]

$$n_v \sim \left(\frac{M_X}{m_{pl}} \right)^{3/2} T^3, \quad (3)$$

which is much larger than the critical density of the universe and would give an enormous cosmic ray flux, unless vortons are extremely stable under quantum decay. On the other hand if the scale for superconductivity m_σ is lower than M_X , the vorton density is reduced to

$$n_v \sim \left(\frac{m_\sigma}{M_X} \right)^{9/2} \left(\frac{M_X}{m_{pl}} \right)^{3/2} T^3, \quad (4)$$

when the condensation is produced in the string friction regime. For $m_\sigma < M_X^2/m_{pl}$ the string radiation regime applies but the consequences are similar. If $m_\sigma \sim 10^9 \text{ GeV}$ this vorton abundance is consistent with the universe critical density.

Taking the matter dominance scaling

$$a/a_0 = (t/t_0)^{2/3}, \quad T \sim 10 \text{ eV } (t_{eq}/t)^{2/3}, \quad (5)$$

and for this order of vorton density, the present cosmic ray flux would be

$$\frac{1}{A} < \frac{d\mathcal{N}}{dt_0} > = \frac{N_c}{\tau_v[yr]} 10^9 \frac{1}{km^2 yr} . \quad (6)$$

Depending on the vorton details which determine its lifetime for the relevant decay mode, if it is of the order of the universe age and expecting $N_c \sim 10$ as the number of UHECR per emitted carrier, Eq.(5) might be consistent with the measured flux $\sim 1/km^2 yr$ for cosmic rays of energy $\geq 10^{19} eV$.

III. Lifetime of Vortons

We may estimate the decay probability of the vorton by a tunneling expression through a barrier of height ΔE and width ΔR

$$\tau_v^{-1} \sim M_v \exp(-\Delta E \Delta R) . \quad (7)$$

It can be evaluated [9] that the vorton mass is $M_v \sim N\eta$ where $N \sim Z$ is the topological or charge number. Its length is $L \sim N\eta^{-1}$ and the maximum number of produced particles is around N .

For the case in which one considers that the loop collapses and disappears, the barrier height ΔE corresponds to the energy which must be supplied to cut the configuration across the area limited by the loop in order to recover the same topology as the vacuum. One may expect therefore $\Delta E \sim N^2\eta$. On the other hand the barrier width ΔR may be estimated by the contraction of the loop to a point, giving rise to the N free particles equivalent to the initial energy of the vorton. In this way $\Delta R \sim N\eta^{-1}$. If this is the dominant decay channel the vorton lifetime

$$\tau_v^{-1} \sim N M_X \exp(-N^3) \sim N \frac{10^{47}}{yr} \exp(-N^3) \quad (8)$$

would be so large that for any reasonable $N \geq 10$ Eq.(2) would give a negligible cosmic ray flux.

But another decay mode is the one in which the vorton emits a carrier conserving angular momentum [10]. To make a more detailed evaluation of the lifetime along this line, the energy of a vorton of radius R is

$$E = 2\pi R\mu + K \frac{N^2}{R} \quad , \quad (9)$$

where the first term comes from the normal string tension $\mu \sim \eta^2$ and the second one from the current and charge contributions $J^2 + Q^2$ with $K < 1$ depending on the nature of the carriers. The minimization with respect to R gives

$$R^* = \sqrt{\frac{K}{2\pi\mu}} N \quad , \quad E^* = 2\sqrt{2\pi K\mu} N \quad . \quad (10)$$

Thinking on the simple case where along the string a charged field σ is oscillating with amplitude σ_0 and a phase which changes in $2\pi N$ around the loop, the decay probability will correspond to Eq.(7) to pass to a $N - 1$ chiral string and one emitted particle. To evaluate the barrier height one has to put $\sigma_0 \rightarrow 0$ along one wavelength and extract one particle with momentum conservation, requiring therefore

$$\Delta E = \Delta V \delta^2 \frac{1}{\eta} + \sqrt{m_\sigma^2 + \left(\frac{N}{R^*}\right)^2} - \frac{N}{R^*} \quad . \quad (11)$$

The increase of potential in the core may be estimated to be $\Delta V \approx m_\sigma^2 \sigma_0^2$ since its minimum is expected to occur there for $|\sigma| = \sigma_0$, the string width $\delta > \eta^{-1}$ for the superconducting case [11] and the momentum for the massless carrier inside the string is N/R^* because the uncertainty principle must be considered for a segment $\sim \eta^{-1}$ both for fermions and bosons condensate.

The particle σ acquires a mass $m_\sigma \approx f\eta$ outside the core through coupling with the neutral field ϕ responsible for the U(1) breaking which generates the string, and keeps the same momentum as inside the core to conserve angular momentum.

The barrier width comes from the separation of the emitted particle up to the position where, always conserving angular momentum, the total energy of the configuration equals that of the original string

$$\sqrt{m_\sigma^2 + \left(\frac{N}{R^* + \Delta R}\right)^2} + 2\sqrt{2\pi K\mu} (N - 1) = 2\sqrt{2\pi K\mu} N \quad , \quad (12)$$

which allows to extract $\Delta R \propto N \eta^{-1}$.

For the use of Eq.(7) we will have now $\Delta E \Delta R \approx b N$. If $m_\sigma \sim 10^9 GeV$ it turns out [9] that $N \sim 10^6$ predicting extremely stable loop. If instead $m_\sigma \sim M_{GUT}$ the number $N \sim 10$ and with $b \sim 15$, which is perfectly possible because of the contribution to ΔE of the first term of Eq.(11) with the expected $\sigma_0 \sim \eta$, the required value $\tau_v \sim a \text{ few } 10^{10} \text{ yr}$ can be obtained to have from Eq.(6) with $N_c = 10$ a flux of the order of one event per km^2 of detector per year.

An objection regarding the use of Eq.(6) for vortons with coinciding scales of string formation and superconducting condensate is that their density should overcome the critical one. However, it must be considered that this statement corresponds to neglecting their quantum decay. In addition, other causes of decrease of vorton density may be the disappearance of zero modes in phase transitions subsequent to their formation [12] and electromagnetic selfinteractions [13]. Therefore, it is not unconceivable that these small vortons are compatible with the universe critical density.

IV. Conclusions

We have seen that small loops of superconducting strings which contain around ten heavy carriers may decay by tunneling producing a flux of high energy cosmic rays compatible with the expected one to be tested in the future by observatories like the Auger Project. This corresponds to coincident scales for formation of strings and superconducting condensate. On the contrary larger loops which might have become superconducting at a lower scale would be so stable that can be excluded as sources of UHECR.

To obtain a more precise prediction of the contribution of decaying vortons two aspects should be refined. One of them is the study of detailed models related to Grand Unified Theories which produce superconducting strings and the calculation of their density taking into account quantum effects and the enhancement or depletion due to the thermal history of the universe after their formation. The other is the precise analysis of the vortons lifetime going beyond the present semiclassical estimation, considering all the involved fields including the GUT gauge bosons and identifying the instantons responsible for the decay of these configurations.

Acknowledgements

We thank Diego Harari for useful discussions.

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